

# ACCRETION RATES IN X-RAY BURSTING SOURCES

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## ABSTRACT

We present estimates for the accretion rates in 13 X-ray bursting sources which exhibit photospheric expansion, basing on theoretical models of stationary, radiatively driven winds from neutron stars. The relatively high values obtained,  $\dot{M}_{acc} \gtrsim 10^{-9} M_{\odot}/yr$ , are in accordance with theoretical limits for unstable helium burning, and, at the same time, almost never exceed the “dynamical” limit for stationary accretion,  $\sim 10 \dot{M}_{Edd}$ . The only exceptions are 1820-30, already known to be a very peculiar object, and 1608-522; there are indications, however, that in both sources, accretion could be non-stationary.

*Subject headings:* accretion, accretion disks – stars: binaries – stars: individual – stars: neutron – X-rays: bursts

Accepted for publication in the Astrophysical Journal

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## I. INTRODUCTION

Low-Mass X-ray Binaries (LMXBs) are widely believed to be powered by the accretion of gas lost by the secondary, main sequence component of the binary system onto a neutron star. This appears to be now a well established point on both observational and theoretical grounds, although the observed X-ray properties of LMXBs can differ substantially from source to source, according to the different physical conditions in the system. The presence of a high neutron star magnetic field can produce a regular modulation in the X-ray emission, as in X-ray pulsators, while other subclasses of sources, in the large family of LMXBs, may be characterized by different accretion scenarios. Within this picture, one of the most important parameters in governing the overall appearance of the source, is certainly the mass transfer rate,  $\dot{M}_{acc}$ , from the secondary onto the neutron star. It has been recently suggested (Kylafis & Xilouris 1993) that Super Soft Sources ultraviolet emission is produced in the very dense, optically thick envelope which shrouds a neutron star accreting close to the maximum allowed rate. In this respect, X-ray bursters, too, should be characterized by quite high values of the accretion rate since unstable nuclear burning, which is responsible for the bursting phenomenon, can take place only if  $\dot{M}_{acc}$  exceeds some definite limit (Fushiki & Lamb 1987; Taam *et al.* 1993). The determination of accretion rates in X-ray bursting sources with photospheric expansion, based on independent arguments, would be quite useful both for testing the consistency of the helium burning scenario, and for shedding light on various aspects of evolution of close binaries. Any direct measurement of mass transfer rates in LMXBs appears to be still beyond the capabilities of present instrumentation and, up to now, the only, indirect, estimates come from the comparison of the binary period variations with existing evolutionary theories (see, for instance, Rappaport *et al.* 1987). In the

present paper we derive accretion rates in LMXBs which show strong X-ray bursts with photospheric expansion. During the expansion/contraction phase, in fact, a supersonic wind is believed to be present and the envelope mass at the beginning of the wind phase can be obtained by confronting the observed spectral parameters with a set of theoretical wind models (Nobili, Turolla & Lapidus 1993); the knowledge of the interburst time will then provide the accretion rate. The analysis of the 13 sources for which sufficient data are available, produced  $\dot{M}_{acc} \gtrsim 10^{-9} M_{\odot}/yr$ , in agreement with the current idea that strong X-ray bursters should be characterized by high values of the mass transfer rate in comparison with other LMXBs.

## II. PHOTOSPHERIC EXPANSION IN X-RAY BURSTERS

The most powerful observed X-ray bursts show a characteristic temporal behavior. Usually the event starts with a sudden increase of the X-ray intensity, with rise times less than one second, followed by a decrease, with a total duration of a few seconds. After the precursor, a noticeable decay of the flux is observed, lasting up to  $\sim 10$  s in the strongest bursts, at the end of which the luminosity can be as low as the persistent one. The main part of the burst then begins. The increase of the X-ray intensity first appears in the soft energy channels, and gradually becomes visible in the harder bands. The color temperature increases while the X-ray luminosity stays nearly constant at its maximum value, commonly associated with the Eddington limit. A direct use of the relation  $4\pi\sigma R_{col}^2 T_{col}^4 = L \sim L_{Edd}$  shows that the typical size of the emitting region,  $R_{col}$ , after having reached a maximum, decreases in this phase until  $R_{col}$  is, again, comparable with the neutron stars radius  $R_*$ . After the blackbody temperature has reached a maximum (often above  $\sim 2$  keV), the decay starts with the progressive decrease of the X-ray flux accompanied by a softening of

the spectrum, while the “color” radius remains approximately constant. The last phase is quite similar to that one observed in weaker, type I, X-ray bursts, where the energy released is below the Eddington limit during all the burst and no expansion is observed.

Photospheric expansion during strong bursts is widely believed to be produced by a supersonic outflow, driven by the large, super-Eddington luminosity released by thermonuclear He burning at the base of the envelope. In a very recent paper Nobili, Turolla & Lapidus (1993, hereafter paper I, see also Lewin, van Paradijs & Taam 1993, hereafter LVPT, for a review of earlier studies on this subject) have presented a more complete model for radiative wind acceleration during strong, type I, X-ray bursts which accounts properly for both energy production by 3- $\alpha$  helium burning and Comptonization heating-cooling in the outflowing envelope. One of the major results obtained in that investigation was the discovery of a lower limit for the mass loss rate  $\dot{M}_{min}$ , below which no stationary, supersonic wind can exist. The existence of such a bound is due to a sort of “preheating” effect and could be of great significance for the determination of some important physical parameters in strong X-ray bursting sources. In paper I, in fact, we suggested that the quasi-stationary expansion/contraction phase, during which  $L \sim L_{Edd}$ , could be thought as a sequence of steady wind models with decreasing  $\dot{M}$  which terminates when  $\dot{M}_{min}$  is reached. By taking this into account and if the maximum and minimum color temperatures in the expansion phase,  $T_{col}^{max}$ ,  $T_{col}^{min}$ , are known from observational data, the initial envelope mass  $M_{env}$  can be derived (see paper I for details); the mass accretion rate  $\dot{M}_{acc}$  follows once the time interval  $\Delta t$  between two successive bursts with photospheric expansion is available. The fitting of the theoretical  $R_{col} - T_{col}$  relation with the the observed one provides also an estimate of the spectral hardening factor  $\gamma$ . In paper I this approach has

been applied to 4U/MXB 1820-30, mainly as a working example of the method.

Photospheric expansion during powerful bursts has been observed so far in 14 sources of type I bursts, and in type II bursts from the Rapid Burster 1730-335 (LVPT), although it can not be excluded that in some cases the physical scenario may differ from that one outlined above. Here we present results for all the bursters for which published data allow a derivation of  $T_{col}^{max}$ ,  $T_{col}^{min}$  and  $\Delta t$ .

### III. INDIVIDUAL SOURCES

In this section we shall review the main observational properties of all sources of type I bursts in which photospheric expansion has been detected. Our primary goal is to extract from observational data the maximum and minimum values of the color temperature during the bursts with radius expansion together with the interburst time. As we discussed in the previous section, in fact, if these three parameters are known both the hardening factor and the accretion rate onto the bursting neutron star can be derived from the sequence of stationary wind models. The set of models we shall use below refers to a neutron star of mass  $M_* = 1.5M_\odot$  and radius  $R_* = 13.5$  km. For 1820-30 there is a strong evidence that the secondary is an evolved, helium-rich star, so helium wind models are used, while, in comparing data relative to all other sources, “solar” composition models seem more appropriate. For each source we derive  $\gamma$ ,  $\dot{M}_{acc}$  and compare the adiabatic cooling time of the envelope,  $t_{cool}$ , with the interburst time. As it was discussed in paper I, accretion can be regarded as stationary only if  $t_{cool} \ll \Delta t$ .

*a) 0748-676*

During 9 observations with EXOSAT a total of 37 bursts were detected (Gottwald *et al.* 1986). Bursts with expansion always had  $\Delta t > 5$  hr, and they

occurred only when the persistent flux was high,  $\sim 2 \times 10^{-9} \text{ erg cm}^{-2} \text{ s}^{-1}$ . In the paper by Gottwald *et al.* the data of all bursts are mixed together, and only average figures of interest for us may be extracted:  $T_{col}^{max} \approx 2.2 \text{ keV}$ , and  $T_{col}^{min} \approx 1.4 \text{ keV}$ . Then  $\gamma = 1.68$  and  $M_{env} = 4 \times 10^{22} \text{ g}$ , with an accretion rate of  $\dot{M}_{acc} \approx 3.5 \times 10^{-8} (5 \text{ hr} / \Delta t) M_{\odot} / \text{yr}$ . The usual assumption that the persistent flux is due to the conversion of gravitational potential energy appears to be justified because the cooling time of the envelope is  $t_{cool} \sim 4 \times 10^3 \text{ s} < \Delta t$  and, therefore, accretion is stationary, contrary to what occurs in 1820-30 (see paper I and section IV).

Gottwald *et al.* (1987) observed also the source in a low state when no expansion occurred during bursts. These observations seem to confirm the suggestion by Fujimoto *et al.* (1987) that incomplete nuclear burning is responsible for bursts with short  $\Delta t$ , while in bursts with expansion (which show larger  $\Delta t$ ) nearly all the fuel is burned out.

#### *b) 1516-569/Cir X-1*

EXOSAT observations (Tennant, Fabian, & Shafer 1986) revealed just one burst with photospheric expansion. The spectral data give  $T_{col}^{max} \approx 2.2 \text{ keV}$ ,  $T_{col}^{min} \approx 1.5 \text{ keV}$ , which implies  $\gamma = 1.68$ ,  $M_{env} \approx 3 \times 10^{22} \text{ g}$ . The time interval separating this burst from the previous one is unknown, but it can be estimated  $\sim 4$  days. The estimated accretion rate  $\dot{M}_{acc} \approx 1.4 \times 10^{-9} M_{\odot} / \text{yr}$  is below the critical value and accretion should be stationary since  $t_{cool} \simeq 2.5 \times 10^3 \text{ s} \ll \Delta t$ .

#### *c) 1608-522*

The observational data of Hakucho (Murakami *et al.* 1987) contain the record of a burst with radial expansion that occurred on April 8, 1980. The bursts frequency in April–May was  $\nu_b = 0.09 \pm 0.03 \text{ hr}^{-1}$ . The blackbody fitting of spectra gives  $T_{col}^{max} \approx 3.5 - 4.0 \text{ keV}$ ,  $T_{col}^{min} \approx 1.2 \text{ keV}$ . The hardening factor

is  $\gamma = 2.67$ , and a quite large value of the envelope mass is obtained,  $M_{env} = 2 \times 10^{23}$  g. The high cooling time of such an envelope,  $t_{cool} \sim 10^5 \text{ s} \gtrsim \Delta t$ , and the high, largely super-Eddington accretion rate  $\dot{M}_{acc} \approx 8 \times 10^{-8} M_{\odot}/\text{yr}$  make the source, at that period of time, more similar to 1820-30 than to the “normal” bursters with  $\dot{M}_{acc} \lesssim \dot{M}_{Edd}$ .

Later observations by Tenma in 1984 indicate a decrease of the accretion rate in this system. Nakamura *et al.* (1989) reported a series of bursts, two of which (G and J in their notation) showed radial expansion. In burst G the fitting temperatures were  $T_{col}^{max} = 2.5$  keV,  $T_{col}^{min} = 1.8$  keV, resulting in  $\gamma = 1.91$  and  $M_{env} = 2.5 \times 10^{22}$  g. In the period of time preceeding burst G, the average accretion rate was  $\dot{M}_{acc} \simeq 6 \times 10^{-9} M_{\odot}/\text{yr}$ . Burst J was stronger, with color temperatures  $T_{col}^{max} = 2.9$  keV and  $T_{col}^{min} = 1.5$  keV implying  $\gamma = 2.21$ ,  $M_{env} = 8 \times 10^{22}$  g and a super-Eddington accretion rate  $\dot{M}_{acc} \simeq 1.7 \times 10^{-8} M_{\odot}/\text{yr}$ . The accretion regime was, probably, stationary in both bursts since  $t_{cool} \sim 1.7 \times 10^3 \text{ s} \ll \Delta t = 6.7 \times 10^4 \text{ s}$  (burst G), and  $t_{cool} \sim 2 \times 10^4 \text{ s} \lesssim \Delta t = 7.4 \times 10^4 \text{ s}$  (burst J).

Photospheric second-range oscillations, observed in 1608-522 during the long ( $\sim 12$  s) flat top of the light curve, are discussed in a separate paper (Lapidus, Nobili & Turolla 1994).

#### *d) 1636-536*

This object is one of most “reliable” sources of bursts and has been extensively observed by Hakucho, Tenma and EXOSAT. As far as Tenma observations are concerned, there is only one burst, denoted as burst H by Inoue *et al.* (1984), which data can enable us to determine  $M_{env}$  and  $\dot{M}_{acc}$ . In all the other 11 bursts they reported, either there is no expansion or (for bursts D and E) the value  $\Delta t$  before the burst with expansion is unknown since observations were not continuous. Burst H had  $T_{col}^{max} \sim 2.9$  keV,  $T_{col}^{min} \sim 2$  keV

which correspond to  $M_{env} \sim 3.2 \times 10^{22}$  g. With an interburst time  $\Delta t \sim 22$  hr, we obtain  $\dot{M}_{acc} \sim 6.4 \times 10^{-9} M_{\odot}/yr$ .

An extensive analysis of numerous bursts from 1636-536 was performed by Lewin *et al.* (1987), using EXOSAT data. Expansion was found in 3 bursts only, those ones with numbers 11, 26 and 27. Unfortunately no blackbody fitting during the expansion/contraction phase was performed for these bursts and the re-examination of archive data may provide valuable informations for this source.

#### *e) 1715-321*

Tenma observations (Tawara, Hayakawa & Kii 1984) have registered only one burst with expansion, and  $\Delta t$  is thus unknown. It may be that there were no bursts in the 3 months preceeding the burst under consideration, but it is also equally possible that  $\Delta t \sim 10$  days, as it has been in 1979. The burst had  $T_{col}^{max} \sim 1.1$  keV,  $T_{col}^{min} \sim 0.25$  keV, corresponding to  $\gamma = 0.8$  and  $M_{env} \sim 5 \times 10^{23}$  g. With  $\Delta t \sim 10$  d, we obtain  $\dot{M}_{acc} \sim 9.2 \times 10^{-9} M_{\odot}/yr$  while for  $\Delta t \sim 3$  months it is  $\dot{M}_{acc} \sim 10^{-9} M_{\odot}/yr$ . The cooling time for such an envelope is  $t_{cool} \sim 10$  days, so the situation may be fairly stationary for both values  $\Delta t$  considered.

On July 20, 1982, Hakucho observed a very long ( $\sim 300$  s) burst with precursor, in which the luminosity stayed at its maximum value for almost 100 s (Tawara *et al.* 1984a). The blackbody fitting gave  $T_{col}^{max} = 3.0 \pm 0.2$  keV,  $T_{col}^{min} = 1.1 \pm 0.1$  keV. After this burst, in 29 days of observations, no events were detected (although the observations were not continuous, the effective observation time was  $\sim 120$  hr). Generally saying, this source shows a weak activity, having produced only 3 bursts in 20 days in 1979 and a total of 4 bursts in 155 days during 1979–82. Therefore, although the precise value of  $\Delta t$  for the burst we consider is unknown, a value  $\sim 10$  d seems to be appropriate.



We obtain  $\gamma = 2.29$ ,  $M_{env} \approx 2 \times 10^{23}$  g and the accretion rate before the burst was then  $\dot{M}_{accr} \approx 3.7 \times 10^{-9} (10d/\Delta t) M_{\odot}/yr$ , of the same order as with Tenma data.

*f) 1724-307/Terzan 2*

The only burst with expansion from this source was, probably, registered by Grindlay *et al.* (1980) during a 30 minute Einstein observation. The blackbody fitting of spectra produced  $T_{col}^{max} \simeq 3.2$  keV,  $T_{col}^{min} \simeq 2$  keV, resulting in the hardening factor  $\gamma = 2.44$  and  $M_{env} \sim 5 \times 10^{22}$  g. The interburst time preceeding this burst is unknown, but after this event EXOSAT did not register any bursts in 12 hr of continuous monitoring. The value of accretion rate,  $\dot{M}_{accr} \sim 10^{-8} \times (1d/\Delta t) M_{\odot}/yr$  may be equally sub- or super-Eddington, and no conclusion can be reached at the present stage.

*g) 1728-337*

The source was extensively observed by SAS-3 in 1976–78, and a total of 60 bursts were registered (Hoffman *et al.* 1980). The average  $\Delta t$  was  $3 \div 8$  hr. In only one of the bursts (on June 8, 1977) the expansion occurred. Before this event there were no bursts in a 56 hr period, although some bursts may have been missed because the Earth occulted the source roughly one-third of the time. The spectral fitting parameters were  $T_{col}^{max} = 2.6$  keV,  $T_{col}^{min} = 1.7$  keV which give  $\gamma = 1.98$ ,  $M_{env} \sim 4 \times 10^{22}$  g and, assuming the 56 hr value as the actual  $\Delta t$ , the accretion rate is  $\dot{M}_{acc} \sim 3 \times 10^{-9} (56hr/\Delta t) M_{\odot}/yr$ , just below the Eddington level. The thermal regime of the envelope between bursts is completely stationary since  $t_{cool} \sim 1.2$  hr.

*h) 1743-29*

The source is one of the Galactic Center X-ray bursters and it was observed with SAS-3. All the bursts reported by Lewin *et al.* (1976) had double and

triple peaks. The average  $\Delta t$  was  $\sim 1.5$  d. Unfortunately, the spectral fitting was impossible due to the poor quality of the data.

*i) 1746-370/NGC 6441*

Sztajno *et al.* (1987) detected 2 bursts with expansion, separated by 8.5 hr, during a continuous 12 hr EXOSAT observation. The spectrum fitting parameters of both bursts are quite similar,  $T_{col}^{max} = 2.2$  keV,  $T_{col}^{min} = 1.2$  keV. The application of our theoretical model yields  $\gamma = 1.68$ ,  $M_{env} \simeq 6.5 \times 10^{22}$  g, and an accretion rate  $\dot{M}_{acc} \simeq 3.4 \times 10^{-8} M_{\odot}/yr$ . The high accretion rate is in agreement with a cooling time scale  $\sim 10^4$  s  $\sim \Delta t$ .

The characteristics of the strongest bursts in 1746-370 seem to be not changing in time. In fact, a re-analysis of 2 bursts observed earlier with SAS-3 (Li & Clark 1977) gives  $T_{col}^{max} = 2.2, 2.4$  keV, values quite similar to those derived from EXOSAT data.

*j) 1812-12*

The observations with Hakucho (Murakami *et al.* 1983) revealed two bursts with photospheric expansion, on 1982, August 18 and 22. The spectrum fitting produced  $T_{col}^{max} \sim 2.5$  keV; the data about the earlier phases of the burst are far poorer and do not allow the determination of  $T_{col}^{min}$ . Assuming, nevertheless, a value of  $T_{col}^{min} \sim 1.2$  keV as characteristic from other similar sources, we obtain  $\gamma = 1.9$ ,  $M_{env} \sim 9 \times 10^{22}$  g and  $\dot{M}_{acc} \sim 3.3 \times 10^{-9} (5d/\Delta t) M_{\odot}/yr$ .

*k) 1820-30/NGC 6624*

The source is located in NGC 6624, and this provides a reliable estimate for its distance of  $6.4 \pm 0.6$  kpc (Vacca, Lewin & van Paradijs 1986). It exhibits a 685-seconds periodicity, first discovered by Stella *et al.* (1987) with EXOSAT, and interpreted as an evidence for orbital motion. The orbital period is the shortest one known in LMXBs (see Parmar & White 1988 for a review) and is

consistent with a scenario in which the secondary is a low-mass, helium-rich degenerate star (Rappaport *et al.* 1987). Data on the time evolution of this period are somewhat controversial. It was observed to decrease over the years 1976–1991 (Sansom *et al.* 1989; Tan *et al.* 1991; van der Klis *et al.* 1993a) with a time scale of  $\sim 10^7$  yr, which might be caused by gravitational acceleration in the cluster potential or by a distant third companion in a hierarchical triple. The standard scenario, involving mass transfer from a Roche lobe-filling degenerate dwarf in an 11-minutes orbit around a neutron star, predicts a secular increase of the orbital period  $> 8.8 \times 10^{-8} \text{ yr}^{-1}$  (Verbunt 1987; Rappaport *et al.* 1987) rather than a decrease. The most recent ROSAT observations (van der Klis *et al.* 1993b) do not provide any evidence of significant period decrease. It has been proposed that the secular variation observed in 1976–1991 could have been dominated by some changes in the position and shape of an occulting bulge on the disk rim. The phase shifts caused by this mechanism could, in principle, mimic the orbital period decrease, while the real period has been indeed increasing, according to the standard theory.

As far as the evidence of photospheric expansion in this source is concerned, there are two series of observations which can provide information about the maximum and minimum color temperatures reached in the expansion phase, and the interburst time. The first is the series of bursts observed by Clark *et al.* (1977) with SAS-3 in May 1975 and March 1976 and the second is the sequence of 7 successive bursts with photospheric expansion observed by Haberl *et al.* (1987) with EXOSAT. The analysis of the latter data was presented in paper I and provided the unusually high values of  $M_{env} \sim 9 \times 10^{23} \text{ g}$  and  $\dot{M}_{acc} \sim 10^{-6} M_{\odot}/\text{yr}$ .

Vacca, Lewin & van Paradijs (1986) reported 6 bursts with photospheric expansion in SAS-3 observations. The satellite had two independent detectors.

In some bursts both of them were providing enough information for the blackbody fitting, while, in other cases, only the data from one detector were of satisfactory quality. The estimates of the accretion rate are summarized in Table 1. The notation N/A stands for cases when  $T_{col}$  was not measured; the bursts are numbered as in Clark *et al.* (1977). In spite of being somewhat lower than the figure obtained from EXOSAT data, the present values  $\dot{M}_{acc}$  are always in excess of the Eddington value for He-rich matter,  $\dot{M}_{Edd} \sim 7 \times 10^{-9} M_{\odot}/yr$ . This confirms the suspicion that MXB 1820-30 is a very peculiar source which shows the highest mass transfer rate between X-ray bursters. Since bursters distinguish themselves among LMXBs because of high accretion rates, MXB 1820-30 is, definitely, one of the observed sources with highest accretion rates. Together with the still unexplained abnormal behavior of the orbital period, our results make this source even more attractive for further investigations.

#### l) 1850-087/NGC 6712

The observations with SAS-3 revealed three bursts from the source, the first two separated by 17 hr and without signs of expansion, and the third, strongest one, with expansion (Hoffman *et al.* 1980). The precise value of  $\Delta t$  for the third burst is unknown, but a value  $\sim 1$  d seems to be appropriate. The spectral fitting produced  $T_{col}^{max} \simeq 2.7$  keV,  $T_{col}^{min} \simeq 1.6$  keV. Then the hardening factor is  $\gamma = 2.1$ , and  $M_{env} = 5 \times 10^{22}$  g. The accretion rate is  $\dot{M}_{accr} \simeq 9 \times 10^{-9} (1d/\Delta t) M_{\odot}/yr$ . Being close to the Eddington limit for He-rich matter, and only twice that one for a pure hydrogen envelope, such an accretion rate seems to be consistent with the fairly low persistent flux.

*m) 1905+000*

Chevalier & Ilovaisky (1990) made a detailed spectral analysis of one burst with photospheric expansion detected during a continuous 19 hr EXOSAT observation. Although being non-perfect, the blackbody fitting gave  $T_{col}^{max} = 3.5 \pm 0.7$  keV,  $T_{col}^{min} = 1.7$  keV, resulting in  $\gamma = 2.67 \pm 0.53$  and  $\dot{M}_{acc} \sim 10^{-8}(1d/\Delta t)M_{\odot}/yr$ . The thermal regime of the envelope should be stationary since  $t_{cool} \sim 10^4$  s.

*n) 2127+119/M15*

One very strong burst with expansion was reported by Dotani *et al.* (1990) and Van Paradijs *et al.* (1990). Similarly to what was observed in 1608-522, a series of photospheric oscillations were detected with Ginga during the first  $\sim 30$  s of the burst in this source; this issue is addressed to in Lapidus *et al.* (1994). The blackbody spectral fit provided  $T_{col}^{max} \simeq 2.8$  keV,  $T_{col}^{min} \simeq 1.4$  keV, although, like in some other sources, the spectra deviated from a blackbody in a way that cannot be described in terms of a spectral hardening alone (see discussion below). Applying our usual technique, we obtain  $\gamma = 2.1$  and  $M_{env} \simeq 8 \times 10^{22}$  g. The expectation time of a burst is unknown, but a value  $\sim$  few days seems to be appropriate. The estimated accretion rate  $\dot{M}_{accr} \simeq 5 \times 10^{-9}(3d/\Delta t)M_{\odot}/yr$  does not exceed, probably, the Eddington level.

## IV. DISCUSSION AND CONCLUSIONS

The results obtained in the previous section for 13 sources which exhibit photospheric expansion are summarized in Table 2. It can be seen from the table that, in several cases, the derived values of the accretion rate exceed the Eddington rate  $\dot{M}_{Edd} \sim 4 \times 10^{-9} M_{\odot}/yr$  for a “solar” composition. Such a result not necessarily contradicts standard steady accretion theories since, assuming spherical accretion, the total power released is  $\sim (GM_*/R_*)\dot{M}_{acc} \sim \dot{M}_{acc}c^2/6$  for a neutron star radius nearly three times the gravitational radius, as in our wind models. This means that accretion rates up to 6 times the critical one are still possible. This limit can be even higher if, as it seems more plausible, an accretion disk is formed around the neutron star. In disk accretion, in fact, only about half of the gravitational energy is released in the vicinity of the star surface (the rest being radiated away in the extended disk), and it is only this part of the energy release which can place a limit on the accretion rate. This argument would bring the upper limit for the permitted value of  $\dot{M}_{acc}$  to  $\sim 10\dot{M}_{Edd}$ . Larger accretion rates are still possible in non-stationary accretion, for which the Eddington limit does not apply; in this case gravitational energy is temporarily stored in the accreted material in the form of internal energy.

We note that, although our estimates of the accretion rate are model dependent, they do not imply any precise accretion scenario, that is to say they hold the same no matter how the gas is accreted onto the neutron star and where it comes from. It is apparent from table 2 also that the main source of uncertainty in the determination of  $\dot{M}_{acc}$  is  $\Delta t$ , which is often poorly known, while the evaluation of both  $\gamma$  and  $M_{env}$  appears to be more reliable. It seems reasonable to divide the sources in three classes, according to the estimated value of  $\dot{M}_{acc}$ : the range  $\dot{M}_{acc} \lesssim \dot{M}_{Edd}$  defines group I,  $\dot{M}_{Edd} \lesssim \dot{M}_{acc} \lesssim 10\dot{M}_{Edd}$  group II and  $\dot{M}_{acc} \gtrsim 10\dot{M}_{Edd}$  group III. Group I contains 4 sources: 1516-569,

1715-321, 1728-337 and 1812-12; in group II there are 8 sources: 0748-676, 1608-522 (as observed with Tenma), 1636-536, 1724-307, 1746-370 (marginally belonging to group III), 1850-87, 1905+000, 2127+119. Out of the 13 sources listed in table 2, only 1820-30 definitely belongs to group III, confirming its peculiar nature, together with 1608-522 (as observed with Hakucho). In paper I it was suggested that the highly super-Eddington accretion rate in 1820-30 could be reconciled with standard accretion scenarios on the basis of the unstationary nature of the accretion process. The comparison of the characteristic time needed to radiate away the gravitational energy release, which increases with  $M_{env}$ , with the interburst time has shown, in fact, that, in this source, the envelope has no time to cool between two successive bursts, and therefore the persistent flux could not be directly related to  $\dot{M}_{acc}$ . The same argument applies to 1608-522 in the “high” state, as observed by Hakucho, when  $t_{cool} \sim 3\Delta t$ . It is remarkable that in all cases where  $\dot{M}_{acc}$  exceeds  $\sim 10\dot{M}_{Edd}$ , it is  $t_{cool} \gtrsim \Delta t$ . This can be regarded as a confirmation of our model because the evaluation of the cooling time is completely independent on  $\Delta t$ . A further evidence is provided by the data of 1746-370, which seems to lie at the border of classes II and III and has  $\dot{M}_{acc} \sim 10\dot{M}_{Edd}$ ,  $t_{cool} \sim \Delta t$ . Theoretical limits on the accretion rate for the onset of the helium thermonuclear runaway were placed by Fushiki & Lamb. According to their analysis of the stability of nuclear burnings in a static, solar composition envelope, a helium flash can be produced only if  $10^{-10} \lesssim \dot{M}/(M_{\odot}/yr) \lesssim 10^{-8}$ . The values we have derived are indeed within this range, with the exception of 1820-30 and, possibly, 1608-522, and this seems to be consistent with a picture in which unstable He burning is responsible for strong bursts with photospheric expansion. We note that, in the case of 1820-30, the accreted material is believed to be helium-rich, so that a straightforward application of Fushiki & Lamb’s results to this source is not appropriate. As

far as 1608-522 is concerned, the accretion rate turns out to be well above  $10^{-8}M_{\odot}/yr$  only in one event, while other two observations provide values in the above range. The present estimates of accretion rates onto bursting neutron stars are also not in contradiction with the models of Taam *et al.* , who followed the time evolution of recurrent hydrogen thermonuclear flashes. They found, in fact, that accretion rates  $\approx 10^{-10}M_{\odot}/yr$  give rise to repeated H flashes while suggesting that unstable He burning may be produced only for larger  $\dot{M}_{acc}$  because the high transfer rate can inhibit convective mixing and increase the envelope cooling time.

A definite improvement on the present method for estimating the accretion rate will come from self-consistent frequency-dependent transfer calculations which are now under way. They will provide, in fact, the hardening ratio for each wind model. This sequence of  $\gamma$ 's will substitute the average constant value of  $\gamma$  used so far, which was itself derived by matching spectral data with the models. The comparison of the computed hardening ratios with the present ones would also provide a further test for the consistency of our approach. We note, however, that the values of  $\gamma$  listed in table 2 are quite reasonable. As we discussed in paper I about 1820-30,  $\gamma \sim 2$  is in good accordance with recent transfer calculations in expanding envelopes (Lapidus 1991) and, for all sources we examined, it is  $1.5 \leq \gamma \leq 2.7$ . The only exceptions are the Tenma observation of 1715-321, which give  $\gamma = 0.8$ , while a “normal” value,  $\sim 2.3$ , was obtained from Hakucho's data. Frequency-dependent calculations will also allow the comparison of the self-consistently computed emerging spectrum with observations. This appears to be of particular relevance for strong bursts in which a pure blackbody fitting was often found to be unsatisfactory. Frequency-dependent radiative transfer calculations in expanding envelopes performed so far (Lapidus 1991; Titarchuk 1993; Turolla, Nobili, Zampieri & Lapidus, in



preparation), show, in fact, that a definite soft excess in addition to the general spectral hardening should be expected.

## **ACKNOWLEDGEMENTS**

We thank Philip Podsiadlowski for useful discussions. One of us (I. L.) gratefully acknowledges support from the Royal Astronomical Society and Consiglio Nazionale delle Ricerche–Gruppo Nazionale di Astronomia.

## REFERENCES

- Clark, G.W., Li, F.K., Canizares, C., Hayakawa, S., Jernigan, G., & Lewin, W.H.G. 1977, MNRAS, 179, 651
- Chevalier, C., & Ilovaisky, S.A. 1990, A&A, 228, 115
- Dotani, T., Inoue, H., Murakami, T., Nagase, F., Tanaka, Y., Tsuru, T., Makishima, K., Ohashi, T., & Corbet, R.H.D. 1990, Nature, 347, 534
- Fujimoto, M.Y., Sztajno, M., Lewin, W.H.G., & Van Paradijs, J. 1987, ApJ, 319, 902
- Fushiki, I., & Lamb, D.Q. 1987, ApJ, 323, L55
- Gottwald, M., Haberl, F., Parmar, A.N., & White, N.E. 1986, ApJ, 308, 213
- Gottwald, M., Haberl, F., Parmar, A.N., & White, N.E. 1987, ApJ, 323, 575
- Grindlay, J.E., Marshall, H.L., Hertz, P., Soltan, A., Weisskopf, M.C., Elsner, R.F., Ghosh, P., Darbo, W., & Sutherland, P.G. 1980, ApJ, 240, L121
- Haberl, F., Stella, L., White, N.E., Friedhorsky, W.C., & Gottwald, M. 1987, ApJ, 314, 266
- Hoffman, J.A., Cominsky, L., & Lewin, W.H.G. 1980, ApJ, 240, L27
- Inoue, H., Waki, I., Koyama, K., Matsuoka, M., Ohashi, T., Tanaka, Y., & Tsunemi, H. 1984, PASJ, 36, 831
- Kylafis, N.D. & Xilouris, E.M. 1993, A&A, 278, L43
- Lapidus, I.I. 1991, ApJ, 377, L93
- Lapidus, I., Nobili, L., & Turolla, R. 1994, ApJ Lett., submitted
- Lewin, W.H.G., Li, F.K., Hoffman, J.A., Doty, J., Buff, J., Clark, G.W., & Rappaport, S. 1976, MNRAS, 177, 93P
- Lewin, W.H.G., Penninx, W., Van Paradijs, J., Damen, E., Sztajno, M., Trümper, J., & Van der Klis, M. 1987, ApJ, 319, 893
- Lewin, W.H.G., Van Paradijs, J., & Taam, R.E. 1993, Space Sci. Rev., 62, 223 (LVPT)

- Li, F.K., & Clark, G.W. 1977, IAU Circular No. 3095
- Murakami, T., Inoue, H., Koyama, K., Makishima, K., Matsuoka, M., Oda, M., Ogawara, Y., Ohashi, T., Makino, F., Shibazaki, N., Tanaka, Y., Hayakawa, S., Kunieda, H., Masai, K., Nagase, F., Tawara, Y., Miyamoto, D.S., Tsunemi, H., Yamashita, K., & Kondo, I. 1983, PASJ, 35, 531
- Murakami, T., Inoue, H., Makishima, K., & Hoshi, R. 1987, PASJ, 39, 879
- Nakamura, N., Dotani, T., Inoue, H., Mitsuda, K., & Tanaka, Y. 1989, PASJ, 41, 617
- Nobili, L., Turolla, R., & Lapidus, I. 1993, ApJ, submitted
- Parmar, A.N. & White, N.E. 1988, Mem.S.A.It., 59, 147
- Rappaport, S., Nelson, L., Joss, P., & Ma, C.-P. 1987, ApJ, 322, 842
- Sansom, A., Watson, M., Makishima, K., & Dotani, T. 1989, PASJ, 41, 591
- Sztajno, M., Fujimoto, M.Y., Van Paradijs, J., Vacca, W.D., Lewin, W.H.G., Penninx, W., & Trümper, J. 1987, MNRAS, 226, 39
- Stella, L., White, N.E., & Priedhorsky, W. 1987, ApJ, 312, L17
- Taam, R.E., Woosley, S.E., Weaver, T.A., & Lamb, D.Q. 1993, ApJ, 413, 324
- Tan, J., Morgan, E., Lewin, W., Penninx, W., van der Klis, M., van Paradijs, J., Makishima, K., Inoue, H., Dotani, T., Mitsuda, K. 1991, ApJ, 374, 291
- Tawara, Y., Kii, T., Hayakawa, S., Kunieda, H., Masai, K., Nagase, F., Inoue, H., Koyama, K., Makino, F., Makishima, K., Matsuoka, M., Murakami, T., Oda, M., Ogawara, Y., Ohashi, T., Shibazaki, N., Tanaka, Y., Miyamoto, S., Tsunemi, H., Yamashita, K., & Kondo, I. 1984a, ApJ, 276, L41
- Tawara, Y., Hayakawa, S., & Kii, T. 1984b, PASJ, 36, 845
- Tennant, A.F., Fabian, A.C., & Shafer, R.A. 1986, MNRAS, 221, 27P
- Titarchuk, L. 1993, ApJ, submitted
- Vacca, W.D., Lewin, W.H.G., & van Paradijs, J. 1986, MNRAS, 220, 339
- Van der Klis, M., Hasinger, G., Dotani, T., Mitsuda, K., Verbunt, F., Murphy,

- B., van Paradijs, J., Belloni, T., Makishima, K., Morgan, E., & Lewin, W.  
1993a, MNRAS, 260, 686
- Van der Klis, M., Hasinger, G., Verbunt, F., van Paradijs, J., Belloni, T., &  
Lewin, W.H.G. 1993b, A&A, 279, L21
- Van Paradijs, J., Dotani, T., Tanaka, Y., & Tsuru, T. 1990, PASJ, 42, 633
- Verbunt, F. 1987, ApJ, 312. L23

Table 1

Accretion Rates in 4U/MXB 1820-30 (SAS-3 data)

Burst #	Detector 1	Detector 2
	$\dot{M}_{acc} (M_{\odot}/yr)$	$\dot{M}_{acc} (M_{\odot}/yr)$
1	$1.7 \times 10^{-7}$	$9.7 \times 10^{-7}$
4	N/A	$1.7 \times 10^{-7}$
6	$4.4 \times 10^{-7}$	$1.2 \times 10^{-6}$
7	$2.8 \times 10^{-7}$	N/A
11	N/A	$1.3 \times 10^{-7}$
20	$1.4 \times 10^{-7}$	$4.2 \times 10^{-7}$

Table 2

Accretion Rates and hardening ratios in X-ray bursting sources

Source	$\dot{M}_{acc}$ ( $M_{\odot}/yr$ )	$\gamma$	Notes
0748-676	$\lesssim 3 \times 10^{-8}$	1.7	only lower limit for $\Delta t$ available
1516-569	$\sim 10^{-9}$	1.7	$\Delta t$ only estimated
1608-522	$8 \times 10^{-8}$	2.7	Hakucho, $t_{cool} \geq \Delta t$
	$6 \times 10^{-9}$	1.9	Tenma burst G
	$2 \times 10^{-8}$	2.2	Tenma burst J
1636-536	$6 \times 10^{-9}$	2.2	Tenma burst H
1715-321	$4 \times 10^{-9}$	2.3	Hakucho
	$10^{-9} \div 10^{-8}$	0.8	Tenma, $\Delta t$ unknown, drastic spectral softening ?
1724-307	$\sim 2 \times 10^{-8}$	2.4	$\Delta t$ only estimated
1728-337	$\lesssim 3 \times 10^{-9}$	2.0	only lower limit for $\Delta t$ available
1746-370	$3 \times 10^{-8}$	1.7	$t_{cool} \sim \Delta t$
1812-12	$\sim 3 \times 10^{-9}$	1.9	$T_{col}^{min}$ unknown
1820-30	$10^{-6}$	1.5	EXOSAT, He models, $t_{cool} \gg \Delta t$
	$10^{-7} \div 10^{-6}$	2.3	SAS-3 (see table 1), He models
1850-87	$9 \times 10^{-9}$	2.1	$\Delta t$ only estimated
1905+000	$\sim 10^{-8}$	2.7	$\Delta t$ unknown
2127+119	$\sim 5 \times 10^{-9}$	2.1	$\Delta t$ unknown